LUNAR ATMOSPHERE

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Abstract

A rarified atmosphere should be present on the moon due to contributions from the solar wind, meteoric volatilization, and internal degassing. Transient contributions to the atmosphere must be produced by rocket gases during lunar missions. These gases may obscure the ambient atmosphere in the vicinity of the landing site for a period of several months following a lunar landing. Of the three natural sources, definite predictions can only be made on the basis of solar wind input. The lunar atmosphere of solar origin is expected to consist mainly of neon, lighter gases being less prevalent because of their lesser concentrations in the solar wind. Daytime neon concentrations are expected near 6×10^4 cm^{-3}, and nighttime concentrations near 1.5×10^6 cm^{-3}.

Introduction

It is usually stated that there is no lunar atmosphere. However, the existence of some trace atmosphere cannot be doubted; it is just that it is so rarified that for most purposes it is valid to assume that it does not exist.

The observational tests so far conceived have not disclosed any detectable atmosphere on the moon. The first test was to look for refraction effects as a star passes behind the moon; from such measurements it was concluded that the lunar atmospheric pressure could not exceed 10^{-4} that of the earth. A more sensitive test involved looking for polarized scattered sunlight just to the dark side of the terminator at quarter moon (Fessenkov, 1943). Dollfus (1952; 1956) further refined this method and found that the lunar atmospheric pressure could not exceed 10^{-6} torr (1 torr = 1 mm hg) or about 10^{-9} that of the earth, still a relatively high upper limit.

The most sensitive earth-based test for a lunar atmosphere is to look for refraction effects on radio stars or radio signals from spacecraft as they are occulted by the moon. Such tests have made it clear that there is no electron cloud greater than 4 x 10 electrons/cm^3 near the lunar surface (Pomalaz-Diaz, 1967), and some deductions have been made from this concerning the amount of neutral atmosphere. However, an assumption must be made concerning the degree of ionization. One assumption associated with earlier observations was that it was the same as the maximum degree of ionization in the earth's atmosphere, about 10^{-3} near the F-2 ionization peak (Elsmore, 1957); this leads to an upper limit of 4 x 10^4 particles/cm^3 in the lunar atmosphere and a surface pressure of less than 1.6 x 10^{-2} torr. However, the physics of ionized gases in the lunar atmosphere is very different from that in the earth's atmosphere, and the degree of ionization mentioned above is unrealistically high for the moon because ion lifetimes there must be very short.

When a neutral atom or molecule is ionized in the lunar atmosphere, the ion must be accelerated by the electric field associated with the motion of the solar wind (Hinton and Taeusch, 1964; Michel, 1964). The electric and magnetic fields associated with the flow of the solar wind are not much affected by the presence of the moon (Ness et al., 1967; Sonett and Colburn, 1967; Johnson and Midgley, 1968, Michel, 1968).

The initial acceleration of newly formed ions is not in the direction of the solar wind, but perpendicular to its imbedded magnetic field; the motion is then deviated by the magnetic field so that the particle moves in a cycloidal motion with an average velocity equal to that component of the solar wind velocity normal to the magnetic field. The acceleration time is about half the gyro period of the ion in the imbedded magnetic field of the solar wind; this is also approximately the time required to move the ion to the lunar surface or to remove it from the vicinity of the moon (because the radius of gyration is comparable to or larger than the lunar radius). For purpose of calculation, a solar wind velocity of 400 km/sec with an imbedded magnetic field of 7 gammas has been assumed (Kavanagh et al., 1970).

The degree of ionization in the lunar atmosphere is obtained by comparing the loss time (half the gyro period) to the time required for solar radiation to ionize a particle — about 10^7 sec for most gases, but nearer 10^6 sec for argon (Hinton and Taeusch, 1964). The results are shown in Table 1 for hydrogen, helium, neon, and argon. Also shown in Table 1 is the upper limit on the surface pressure inferred from the radio observations, based on the degree of ionization shown in the table and the observed upper limit of 40 electrons or ions/cm^3 near the moon. Thus the observational evidence does not preclude the presence on the moon of an atmosphere with a surface pressure near 10^{-10} torr.

Diurnal Variations

The concentrations of gas on the sunlit and dark sides of the moon should not be the same. To consider the distribution of gas over the moon, it is convenient to consider the lunar surface as comprising three zones. The first zone, consisting of that quarter of the lunar surface over which the solar zenith angle is less than 60°, is characterized by a temperature near 370°K. The second zone, also consisting of a quarter of the lunar surface but with solar zenith angle between 60° and 90°, is characterized by temperatures between about 100° and 370°K. The third zone consists of the dark half of the lunar surface and it is characterized by a temperature near 100°K. An analysis of the diffusion of gas over the lunar surface indicates that the equilibrium concentration for non-condensible gases heavier than helium should vary as $T^{-5/2}$ (Hodges and Johnson, 1968). For gases governed by the $T^{-5/2}$ law, there is about twice as much atmosphere over the second zone as over the first. The third zone has 14 times as much atmosphere over it as over the first zone, or about 5 times as much as over zones one and two together. (The concentration over the dark area is about 26 times greater than over the warmest area, but the lesser scale height reduces the ratio of the amounts of gas over unit areas to a factor of 7.)

Some of the gases probably condense or adhere to the cold lunar surface on the dark side. As the surface is heated while passing through the sunrise terminator, the adsorbed gases will tend to be released, and the sunrise terminator likely acts as a gas source.

Escape of Lunar Atmosphere

It has been a generally acceptable concept to regard the moon as having no atmosphere because escape processes exist that can remove it. Because the moon is a relatively small body, velocity of escape from it is relatively low (2.4 km/sec), and light molecules can escape rapidly just by virtue of their thermal velocities. Other escape mechanisms are provided by interaction with the solar wind after atmospheric particles undergo photoionization, and by collisions with solar wind particles.

(a) Thermal Escape

The time constant for thermal escape from an exosphere (Biutner, 1958; 1959) is:

$$\tau = \frac{1}{g}\left(\frac{2\pi kT}{m}\right)^{1/2} \frac{e^{E}}{1+E}$$

where $E = mgr/kT = (v_{esc}/\alpha)^2$ is the square of the ratio of the escape velocity to the most probably thermal velocity α, m the molecular mass, g the acceleration of gravity, r the radius of the moon, k the Boltzman constant, and T the temperature. Results are presented in Table 2 for the escape of H, H_2, He, Ne, and Ar where the lunar surface temperature is taken to be 370°K.

The time constants for thermal escape of atomic and molecular hydrogen are very short, and they are short even at a temperature of 100°K, characteristic of the cool side of the moon; the rapid escape reduces the tendency for such light gases to concentrate on the cool side of the moon. Helium escape at 100°K is not so rapid as to eliminate a cool side increase, but the increase is not as great as $T^{-5/2}$, which is characteristic of heavier gases.

The time constants shown in Table 2 for neon and argon should be increased if they are to be descriptive of the moon as a whole because thermal escape of these gases is negligible for all but the warmest quarter of the moon's surface. Since the $T^{-5/2}$ law indicates that the amount of atmosphere over the warmest quarter of the lunar surface is 1/17 of the total atmosphere, the factor by which the time constants should be increased to be characteristic of the entire lunar atmosphere is 17. To be characteristic of just that part of the atmosphere over the sunlit half of the moon, the time constants should be increased by a factor of 3 as only 1/3 of the gas over this half of the moon is in the warmest region from which escape is effective.

The thermal escape time for neon from the moon, taking the nighttime reservoir into account, is about three thousand years, and for argon, more than geologic time. This circumstance has led in the past to speculation that there might be a significant residual atmosphere of heavy gases (argon, krypton and xenon) on the moon (Edwards and Borst, 1958; Herring and Licht, 1959). However, this is unlikely because another loss process, associated with ionization, acts more rapidly than thermal escape to remove heavy gases.

(b) Loss through Photoionization

If a gas particle near the moon becomes ionized, it then undergoes acceleration due to the electric field associated with the motion of the solar wind. These particles are either lost to space or directed back to the lunar surface. Most of those particles that are driven to the lunar surface attain only a very small fraction of solar wind velocity because they are accelerated only a relatively short distance, compared to a gyro radius, before they strike the surface. Nearly half of the newly ionized particles are accelerated to the lunar surface where they undergo neutralization and later are restored to the atmosphere. However, the other half will not strike the lunar surface but instead will be carried away from the lunar vicinity by the flow of the solar wind. The average lifetime against loss by this process depends mainly on the time required for solar radiation to ionize a particle, which is about 10^7 sec (10^6 sec for argon). Since about half of the ionized particles are convected to the lunar surface, the time constant for escape for that part of the gas cloud over the illuminated half of the moon is about 2×10^7 sec. Taking the nighttime reservoir into account, the time constant is about 10^8 sec or 3 years (10^7 sec for argon), much shorter than the thermal escape times for neon and heavier gases.

(c) Loss by Collision with Solar Wind Particles

Hinton and Taeusch (1964) have considered both elastic collisions and charge-exchange collisions between the solar wind and lunar atmospheric particles. Except for hydrogen, the collision times are longer than the ionization times for normal values of solar wind parameters. Charge-exchange collisions with hydrogen atoms are particularly rapid, but they do not influence the problem because the thermal escape time for hydrogen is very short, much less than either the charge-exchange or photoionization lifetime.

Source of Lunar Atmosphere

There can be both internal and external sources of lunar atmosphere. The internal source is degassing from the interior, either by constant diffusion through the lunar surface or by intermittent release from active vents. The external sources are the solar wind and vaporization during meteoric impacts.

(a) Internal Release

The earth's atmosphere and oceans have been released from the earth's interior by degassing. The average rates of release of gases are shown in Table 3 (Johnson, 1969). If similar rates of release were to prevail on the moon, a significant atmosphere could accumulate. The accumulation lifetime on the sunlit side for N_2 and the noble gases is twice the ionization lifetime, or 2×10^7 sec (assuming that half the newly formed ions escape and half are swept back to the lunar surface). For H_2O, photodissociation occurs much more rapidly than photionization, the dissociation lifetime being about 3×10^4 sec; for CO_2, the photodissociation lifetime is about 10^7 sec. Table 4 shows the accumulation of atmosphere to be expected for release rates comparable to those that exist on earth. The figures given in Table 4 for total gas are the products of the release rates and the lifetimes for the gases over the sunlit portion of the moon; longer lifetimes and greater quantities of gas would apply on the dark side. The surface concentration in Table 4 has been obtained from the total gas by dividing by the scale height, $H = kT/mg$, assuming a temperature of 370^oK. The results indicate that there might be a significant lunar atmosphere of internal origin (say 10^{-11} torr) even if the release rates were lower than on earth by several orders of magnitude.

Some transient luminous events have been recorded on the moon, especially near the Cobra Head (Middlehurst, 1967). This has frequently been interpreted as an intermittent gas release from the lunar interior, but the luminesence mechanism has not been satisfactorily explained. Recent observations of recurrent seismic activity that occurs when the moon is near perigee suggest that tidal forces disturb the moon and produce seismic disturbances in the Frau Mauro region (Latham et al., 1971); further, a release of gas may be associated with these disturbances.

(b) Solar Wind

The solar wind impinges directly on the lunar surface and constitutes a certain source of lunar atmosphere. Its relative composition is variable and not very well known. Robbins et al. (1970) report an average concentration of helium relative to hydrogen less than the cosmic ratio -- 0.037 compared to 0.082. Bame et al. (1970) report the following relative concentrations: H, 5000; He, 150; O, 1.00; Si, 0.21; Fe, 0.17. Compared to cosmic abundances 500, 410, 4.5, 0.21, 0.17 (Cameron, 1969), it is seen that in the solar wind helium and oxygen are depressed by factors of 0.37 and 0.22 respectively, but that silicon and iron are present in normal cosmic abundance relative to hydrogen. On the basis of these results, cosmic abundances have been accepted for solar wind composition in this review.

The solar wind should become neutralized on the lunar surface and, after saturating the surface, be released as a neutral gas. Although gases may be trapped at the surface by adsorption for some time, eventually the rate of release should become equal to the rate at which solar wind particles impinge. The gas concentrations that result near the moon then depend upon the loss processes. Expected concentrations are shown in Table 5. The total gas in a vertical column is obtained by multiplying the solar wind flux by the escape time, which is the thermal escape time for H and He and the ionization escape time for neon and heavier gases. The surface concentration is obtained by dividing the total gas in a column by the scale height. The concentrations shown are expected daytime values; nighttime values should be about a factor of 26 greater except for hydrogen and helium. Note that the predominant gas of solar origin to be expected on the moon is neon. Lighter gases should be less prevalent because of their more rapid escape due to thermal motion, and heavier gases less prevalent because of their lesser abundances in the solar wind. Further, the heavy gases may not have saturated the lunar surface, in which case their rate of release from the lunar surface may be lower than indicated.

(c) Meteoric Impact

Meteoric impact on the lunar surface will release gas by vaporization. If one accepts an inflow rate of 10^{-6} impacts/cm^2-sec with mass 2×10^{-9} g, the mass involved is 2×10^{-19} g/cm^2-sec. The mass of material volatilized is very speculative, and most components undoubtedly condense rapidly. If the meteoric influx mass is provisionally accepted as equal to the mass of volatiles produced, a source of about

3×10^3 molecules/cm^2-sec is produced, rather small (about 10^{-5}) by comparison with the solar wind input. However, the uncertainty is so great as to leave meteoric volatilization a possibly significant source.

Possibilities for Orbital Measurements

If measurements of the lunar atmosphere are to be made in a lunar orbiter, it is advantageous to use as low an orbital altitude as possible because the gas is increasingly rarified at higher altitudes. The Apollo Command and Service Module on early missions orbited near 100 km altitude, but on later missions this altitude may be reduced to about 10 km. Table 6 shows the concentrations of neon and argon to be expected on the day and night sides due to the solar wind input, assuming a 26 times build up of surface concentration on the nighttime side.

The tendency for a nighttime build up in concentration has disappeared at 100-km altitude for neon, because the more rapid fall off in concentration with altitude at night than during the daytime nearly compensates for the surface build up in the cold area. In the case of a heavier gas like argon, the nighttime concentrations at 100 km are very low. For a light gas like helium, the fall off with altitude is much less important, but here the migration to the cold region has not been predicted because of the very rapid thermal escape of helium.

Contaminant Gases

Because the lunar atmosphere is so tenuous, the gases released from the Apollo rocket motors may contribute significantly to the lunar atmosphere. Gases released from the Lunar Module and the astronauts' space suits during the surface operations may substantially overwhelm and mask the ambient atmosphere locally. On lunar orbit insertion of the Command Module, about 10 tons of exhaust gas are released on the backside of the moon, but the combination of vehicle velocity and exhaust velocity exceeds escape velocity, so most of this gas is lost to space. During the descent operation, about 7.5 tons of exhaust gas are released, the greater part of which must be lost to space, but the last ton or so of which is directed at the lunar surface near the landing site. Upon leaving lunar orbit for return to earth, about 5 tons of exhaust gases are ejected on the backside of the moon with the vehicle velocity and exhaust velocity opposing one another, so that the gases largely fall to the lunar surface (Michel, private communication).

The volatiles released near the lunar surface in the descent, surface, and ascent operations total about 3 tons, and the number of contaminant molecules is near 10^{29}, estimated to be 36% H_2O, 32% N_2, 13% H_2, 9.6% CO, 3.7% CO_2, 1.9% H, and 1.6% OH (Aronowitz et al., 1968). The gas release on the back side of the moon upon departure from lunar orbit is about 5 tons. The total contribution to the lunar atmosphere from these two operations is near 3×10^{29} particles. This is equal in number to all the solar wind particles impinging on the entire lunar surface in 10^4 sec or about three hours. Spread uniformly over the lunar surface, this amounts to 10^{12} particles/cm^2 or about 10^5 particles/cm^3 for scale heights near 100 km. This corresponds to a pressure of 2.5×10^{-12} torr and is undoubtedly an overestimate since much of the released exhaust gas must freeze out on the dark side of the moon rather than diffuse uniformly over the lunar surface.

During the Apollo ascent operation, the instrumentation left on the lunar surface is exposed to a very modest blast as the Ascent Stage departs. The flow of exhaust gases is about 5 kg/sec and the velocity about 1 km/sec; the mass flow 100 m away from the Lunar Module in the vicinity of the instrumentation is 8×10^{-6} g/cm^2-sec, assuming that at this distance the exhaust blast is spread equally over the upper hemisphere. This generates a dynamic pressure of 0.8 dyne/cm^2 or 10^{-3} torr. This is a directed pressure; surfaces facing away from the Lunar Module experience a much lower pressure. The gas density at 100 m is about 10^{-10} g/cm^3, for which the mean free path is short enough (~ 1 m) to cause considerable scattering, and the pressure seen by a surface facing away from the Lunar Module might approach a modest fraction of the dynamic value cited above.

A similar environment is produced by the approach of an astronaut. Water is evaporated at a rate of about 0.3 g/sec from his life-support back pack, and if this expands spherically from the source, a pressure of about 10^{-4} torr will be produced at a distance of 1 m, or 10^{-6} torr at 10 m.

When the Ascent Stage is depressurized, gas (mainly oxygen) is released, about 3 kg in 10^{2} sec, or a rate near 30 g/sec. This produces a directed pressure near the instrumentation package of about 10^{-6} torr. If a gas particle strikes the surface, rebounds, and then strikes the surface again without colliding with another particle, the average distance traveled is comparable to the scale height for the particle (approximately 100 km). At a distance of 100 m from the Lunar Module, the mean free path for gas released on depressurization is approximately equal to 100 m, so backscatter should be relatively small in this case, unlike that of ascent stage burning.

The most important aspect of the contamination problem is probably the adsorption of exhaust gas on the lunar surface and its later slow release. The exhaust gases directed at the lunar surface near the landing site approximate a ton in mass, but the proportion of the gas that becomes adsorbed at the surface is highly speculative. We arbitrarily assume here that the fraction adsorbed is 10^{-3}, or that the mass adsorbed is 10^{3} g. Equally speculative is the time required for the adsorbed gas to be released, and we characterize the release time in seconds as τ. The rate of release of adsorbed gas from the vicinity of the Lunar Module at time t is then:

$$\frac{10^3}{\tau} e^{-t/\tau} \text{ g/sec}$$

This will give rise to a mass flow at a distance of 100 m of

$$\frac{10^{-5}}{2\pi \tau} e^{-t/\tau} \text{ g/cm}^2\text{-sec}$$

assuming uniformity over a hemisphere. If the released gases have a thermal velocity of 300 m/sec, then the gas density at 100 m is

$$\frac{10^{-9}}{6\pi \tau} e^{-t/\tau} \text{ g/cm}^3$$

For a molecular weight of 18, this corresponds approximately to a particle concentration of

$$\frac{1.6 \times 10^{12}}{\tau} e^{-t/\tau} \text{ particles/cm}^3$$

The concentrations to be expected after one day and ten days for several time constants (and 10^3 g adsorbed gas) are shown in Table 7. Note that if the adsorption retention time is short ($< 10^4$ sec), the contamination is insignificant after a day. If the retention time is long ($> 10^5$ sec), the initial contamination a few minutes after lift off is much smaller than for the rapid release, but the rate of improvement is much slower and contamination may prove a problem for several months.

Measurements

A cold cathode ionization gage was included in the instrumentation packages on Apollo 12 and 14, and a few data have been obtained at this writing (Johnson, Evans and Carroll, 1970; 1971). On both missions, the gage was turned on shortly after the conclusion of the first period of extravehicular activity (EVA), and the initial readings were near 10^{-6} torr, either because of gas adsorbed inside the gage or because of gas adsorbed on the lunar surface as a result of the landing operation. The gage reading fell gradually to the vicinity of 10^{-8} torr at the time of preparation for the second EVA. Upon depressurization for the EVA, the pressure at the gage increased by almost an order of magnitude due to the released gas, in reasonable agreement with predictions. During the second EVA on Apollo 12, Astronaut Conrad approached the gage and its indication went off scale ($> 10^{-6}$ torr) due to the release of water vapor from his life support system. After his departure from the immediate vicinity, the pressure fell again to 10^{-8} torr.

During the lunar night, the gas concentrations fell to about 2×10^5 particles/cm^3, increasing at sunrise to about 2×10^7. The low nighttime values indicate that contaminant gases freeze out at the nighttime temperature near 100°K, and the rise at sunrise is undoubtedly due at least in part to the release of contaminant gases upon heating the lunar surface. The fact that the nighttime concentrations are lower than the predicted neon concentrations due to the solar wind suggests that the lunar surface has not become saturated with neon.

Several gas clouds have been observed, strongly suggestive of impulsive releases of gases either from the lunar interior or from meteoric impact.

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TABLE 1

Ion properties, degree of ionization in the lunar atmosphere, and the radio limit on lunar atmospheric pressure.

	H	H_2	He	Ne	Ar
Approx. ion gyro radius, km	6×10^{2}	1.2×10^{3}	2.4×10^{3}	1.2×10^{4}	2.4×10^{4}
Ion gyro period, sec	10	20	40	200	400
Ionization time, sec	10^{7}	10^{7}	10^{7}	10^{7}	10^{6}
Degree of ionization	5×10^{-7}	10^{-6}	2×10^{-6}	10^{-5}	2×10^{-4}
Radio limit on pressure, 10^{-10} torr	28	16	8	1.6	0.08

TABLE 2

Thermal escape time τ for lunar gases when the temperature is 370°K. M is molecular weight and E is the square of the ratio of the escape velocity to the most probable thermal velocity.

	M	E	τ
H	1	0.95	3.5×10^3 s
H_2	2	1.90	4.3×10^3 s
He	4	3.80	1.2×10^4 s
Ne	20	19	1.9×10^2 yr
A	40	38	1.3×10^{10} yr

TABLE 3

Average rates of release over geologic time of gases from the earth's interior.

H_2O	10^{11} molecules/cm^2-sec
CO_2	6×10^9
N_2	2×10^8
Ne	3×10^2
A	2×10^6
Kr	2×10^2
Xe	1.5×10

TABLE 4

Expected amounts of lunar atmosphere near the subsolar point if gases are released at the same rate per unit area as the average rate on earth.

Gas	H_2O	CO_2	N_2	A	Ne	Kr	Xe
Lifetime, s	$3x10^4$	10^7	$2x10^7$	$2x10^6$	$2x10^7$	$2x10^7$	$2x10^7$
Total gas, molecules/cm^2	$3x10^{15}$	$6x10^{16}$	$4x10^{15}$	$4x10^{12}$	$6x10^9$	$4x10^9$	$3x10^9$
Scale Height, km	111	45	70	50	100	25	15
Surface concentration, molecules/cm^3	$3x10^8$	$1.3x10^{10}$	$5.6x10^8$	$8x10^5$	$6x10^2$	$1.6x10^3$	$2x10^2$
Pressure, torr	10^{-8}	$4x10^{-7}$	$2x10^{-8}$	$3x10^{-11}$	$2x10^{-14}$	$5x10^{-14}$	$7x10^{-15}$

TABLE 5

Expected amounts of lunar atmosphere near subsolar point due to solar wind impingement on lunar surface.

	H	He	Ne	A	Kr	Xe
Solar wind flux, atoms/cm^2 -sec	$3x10^8$	$3x10^7$	$3x10^4$	$3x10^3$	1	0.1
Escape time, sec	$3.5x10^3$	10^4	$2x10^7$	$2x10^6$	$2x10^7$	$2x10^7$
Total gas, atoms/cm^2-sec	10^{12}	$3x10^{11}$	$6x10^{11}$	$6x10^9$	$2x10^7$	$2x10^6$
Scale height, km	2000	500	100	50	25	15
Surface concentration, molecules/cm^3	$5x10^3$	$6x10^3$	$6x10^4$	$1.2x10^3$	8	1.3
Surface pressure, torr	$1.6x10^{-13}$	$2x10^{-13}$	$2x10^{-12}$	$4x10^{-14}$	$3x10^{-16}$	$4x10^{-17}$

TABLE 6

Expected concentrations per cubic centimeter of neo and argon at the lunar surface and at 10 km and 100 km above the lunar surface due to solar wind source.

	Neon		Argon	
	Day	Night	Day	Night
Surface	6×10^4	1.5×10^6	1.2×10^3	3×10^4
10 km	6×10^4	10^6	10^3	10^4
100 km	2×10^4	3×10^4	2×10^2	15

TABLE 7

Concentrations and pressures 100 m from the Lunar Module for 1 kg adsorbed rocket exhaust released with time constant τ.

Time Constant τ, sec	10^3	10^4	10^5	10^6
Initial concentration, cm^{-3}	$1.6 x 10^9$	$1.6 x 10^8$	$1.6 x 10^7$	$1.6 x 10^6$
Concentration after 1 day, cm^{-3}	10^1	10^4	10^7	$1.5 x 10^6$
Concentration after 10 days, cm^{-3}	10^{-3}	1	10^3	$0.8 x 10^6$
Initial Pressure, torr	$4 x 10^{-8}$	$4 x 10^{-9}$	$4 x 10^{-10}$	$4 x 10^{-11}$
Pressure after 1 day, torr		$< 10^{-12}$	$2.5 x 10^{-10}$	$4 x 10^{-11}$
Pressure after 10 days, torr			$< 10^{-13}$	$2 x 10^{-11}$

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